Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 11, Issue 1 / 2026, pp. 59 - 70
http://doi.org/10.56958/jesi.2026.11.1.59

A. Mechanical Engineering

Received ***28 October 2025*** *Accepted* ***11 March 2026***
Received in revised form ***14 January 2026***

Influence of impact energy level and composite thickness on impact characteristics

LORENA DELEANU[1,2]*, GEORGE CĂTĂLIN CRISTEA[3], IOANA GABRIELA CHIRACU[1], GEORGE GHIOCEL OJOC[4], ALEXANDRU VIOREL VASILIU[1], CLAUDIU MARTIN[1]

[1]„Dunarea de Jos" University, Center of Excellence in Polymer Processing (CE-PP), 47 Domneasca, 800008, Galati, Romania
[2]Technical Sciences Academy of Romania, 26 Dacia, 030167 Bucharest, Romania
[3]National Institute for Aero-Space Research (INCAS) „Elie Carafoli", 220 Iuliu Maniu, 061126 Bucharest, Romania,
[4]Autonomous Flight Technologies, 1 Aeroportului, 077060 Clinceni, Romania

Abstract. This paper presents the influence of impact energy level and the composite thickness on the impact characteristics. The composite is made of stratified quadriaxial glass fiber prepeg layers (0°/+45°/90°/-45°), from Castro Composites (Spain), and an epoxy resin as matrix (SikaBiresin® CR82 with the hardener CH80-2), from Sika Group (Austria). This research study has as input parameters: the number of quadriaxial prepreg layers (6, 8 and 10, respectively), impact energy of 45 J, 100 J and 150 J, respectively. The constant parameters were the impact velocity (approx. 4 m/s) and the diameter of the hemispherical hard steel impactor of 16 mm. Tests were carried out on Instron CEAST 9340 machine and at least three tests with close results are presented. There was discussed the influence of impact energy and composite thickness on the maximum force (F_{max}) during impact, time to F_{max} and duration of impact, t_f. The value of impact energy was decisive in determining the extent of damage. At low energy level (45 J), the response of composites was predominantly elastic, with limited delamination or matrix cracking, while at 150 J severe damage was observed, including yarn fracture and total penetration for the thinner composite. The intermediate level of 100 J revealed the transition zone, where matrix–fiber decohesion and delamination became more pronounced.

Keywords: quadriaxial glass fiber prepeg, epoxy resin, impact test, composite, maximum force under impact, impact velocity, failure under impact, penetration.

*Correspondence address: lorena.deleanu@ugal.ro

1. Introduction

Composite materials reinforced with glass fibers are widely used in marine [1], aerospace [2], and automotive structures [3] due to their high strength-to-weight ratio, corrosion resistance, and tailored mechanical properties. However, one of the most critical aspects of their performance is their behavior under impact loading, which can cause complex damage mechanisms such as matrix cracking, fiber breakage, and delamination [4]. The study of impact response is essential for improving the safety and reliability of structures exposed to accidental or repeated impact conditions.

Previous research has highlighted the strong dependence of impact characteristics on both the impact energy level and the thickness of the laminate. Naresh et al. [5], investigated the effect of high strain rates on glass fiber reinforced epoxy laminates and demonstrated that increasing impact energy significantly accelerates damage propagation, while thicker laminates exhibit higher resistance to penetration. Similarly, Camanho P. P. and Dávila, C. G [1], developed a mixed-mode decohesion finite element approach that emphasized the role of delamination in energy dissipation during impact.

Experimental studies have also confirmed that the number of layers and stacking sequence strongly affect maximum force and absorbed energy during low-velocity impacts. Chu, Y., Min, S. and Chen, X. [7], showed that inter-yarn friction plays a key role in the progressive failure of woven fabrics under ballistic impacts, influencing both load transfer and delamination initiation. In another contribution, Ingle S. et al. [8], analyzed how material properties and inter-yarn friction levels affect ballistic energy absorption, underlining the importance of mesoscale mechanisms in impact resistance. More recently, Meyer C. S. et al. [9], performed mesoscale modeling of ballistic impact experiments on plain weave composites and concluded that laminate thickness has a direct effect on delaying complete penetration by redistributing stresses across multiple yarn systems.

In marine composites, glass-fiber fabrics remain the dominant reinforcement; both E-glass and S-glass are widely available, with S-glass typically costing more due to its enhanced properties [10]. Matrices are commonly polyester, vinyl ester, or epoxy. Quadriaxial fabrics are extensively employed across hulls, decks, superstructures, and internal components because their multi-directional reinforcement provides impact resistance, stiffness, and durability. By contrast, unidirectional reinforcements are selected where ultra-high laminate performance is required [11].

Despite these advances, fewer studies have systematically compared the combined influence of impact energy level and laminate thickness in quadriaxial composites, which are increasingly relevant in marine and aeronautical applications. This paper addresses this gap by investigating the behavior of quadriaxial glass fiber/epoxy composites with varying thicknesses (6, 8, and 10 layers) subjected to different impact energies (45 J, 100 J, and 150 J). The results provide insights into the correlation between energy level, thickness, maximum impact force, displacement, and failure characteristics.

2. The composite and the testing equipment

A defining advantage of statistically designed experiments is that they assess the joint influence of multiple factors on system performance by varying them simultaneously, which yields clearer insight into system behavior and potential synergies among variables. This strategy is generally superior to a sequence of single-factor trials, and, for practicality, most designs restrict each factor to two or three levels, with four or five used only sparingly.

The fabric used here comprises four sub-layers oriented 0°/+45°/90°/−45°, conferring quasi-isotropic behavior from the outset. The material (1200 g/m² Quadriaxial Glass Cloth, code WTVQX1200-1 E-glass, Q1200E10Q) was supplied by Castro Composites (Spain) [12]. The matrix system was the two-component epoxy SikaBiresin® CR82 with CH80-2 hardener [13]. Strict adherence to the manufacturer's mixing ratio is essential to meet performance targets; thermal and mechanical properties also depend on the post-cure. SikaBiresin® CR82 is suitable for hand lay-up and is certified by Germanischer Lloyd. Recommended processing temperatures are 18–35 °C [13].

The curing schedule depends on thickness, fiber volume, and resin reactivity. In this work, a heating rate of ~0.2 °C/min to ~10 °C below T_g was followed by a 2–12 h isothermal hold and cooling at ~0.5 °C/min. With CH80-2, core temperatures may briefly reach ~200 °C before returning to room temperature within ~5–6 h; viscosity evolution requires completing lay-up within about one hour. Despite being time-consuming, hand lay-up remains a reliable route for prototyping and small-batch manufacture [14].

Laboratory processing targeted composite plates suitable for marine use. The mold was treated with CIREX CP-10 (produced by Airétec, Amiens, France, and supplied by RomPolimer Composites SA, Romania) [15], [16] a release wax to form a thin monomolecular barrier. Each ply was manually impregnated, consolidated under a uniform pressure of 0.5–0.7 MPa for at least 8 h, demolded, and naturally aged for 7 days at 20–23 °C; an additional post-cure at 60 °C for 6 h ensured through-thickness crosslinking. Three plate variants (300 mm × 300 mm) with identical constituents but different thicknesses were fabricated: Q-g-6, Q-g-8, and Q-g-10 (6, 8, and 10 quadriaxial prepeg layers, respectively).

Low-velocity impact tests were performed on an Instron CEAST 9350 drop-weight tower (INCAS Bucharest), using a 16 mm hemispherical steel striker [17]. Square specimens (90 mm × 90 mm x ~8 mm thickness) were tested at nominal energies of 45 J, 100 J, and 150 J, corresponding to ~4.32–4.42 m/s. Because specimen size can affect measured response, results should be interpreted with scaling in mind. Earlier work on size and scale effects showed that characterization on small coupons may not fully represent larger components [18], and subsequent impact studies reported scaling validity primarily within the elastic regime, with larger specimens failing at lower loads/ displacements but absorbing more energy prior to fiber rupture [18]. Each impact test condition was repeated three times. Outliers were replaced until at least three consistent curves remained, yielding good repeatability. The first force peak is attributed to the onset of delamination, while the oscillatory features of the force–displacement response reflect typical composite behavior, with minor peaks linked to localized fiber, ply, or sub-layer failures.

In Figure 1, it can be observed that increasing the impact energy from 45 J to 150 J results in a significant rise in peak force and a longer impact duration.

For the 6-layer composites, the 150 J case shows early failure and strength reduction, whereas for the 8- and 10-layer composites the curves appear more uniform and reproducible, indicating a more stable performance. At the same energy level, thicker composites (10 layers) reach higher peak forces compared to 8- and 6-layer laminates, confirming the effect of thickness in enhancing stiffness and load-bearing capacity.

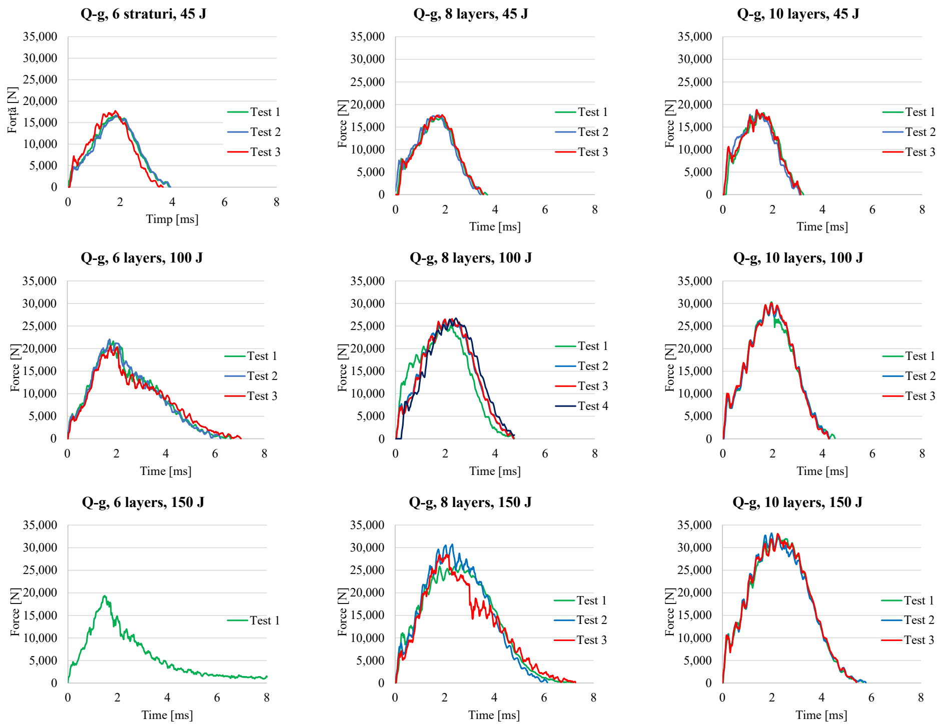

Fig. 1. Force–time curves for quadriaxial glass fiber composites with 6, 8, and 10 layers, at impact energies of 45 J, 100 J, and 150 J.

It is also noticeable that for 45 J, all types of composites behave similarly, with minor differences between the 6-, 8-, and 10-layer laminates. At higher energies, however, the differences become more pronounced: composites with fewer layers show a sharper drop in resistance after reaching the peak force, while the 10-layer configuration maintains a higher capacity to dissipate energy before failure.

In Figure 2, the absorbed energy increases as the impact energy level rises. At 45 J, differences between the three thicknesses are minimal, with all specimens being able to absorb energy without major damage. At 100 J, the 6-layer composites begin to show limitations in absorption capacity, while the 8- and 10-layer laminates display smoother curves and more efficient energy dissipation. At 150 J, only the thicker laminates manage to absorb nearly all the input energy, while the 6-layer samples approach their critical failure threshold.

This highlights the essential role of thickness: the 10-layer plates demonstrate superior absorption capacity, confirming that thicker laminates are more tolerant under severe impacts. By contrast, the 6-layer composites fail earlier, losing part of the energy through localized damage.

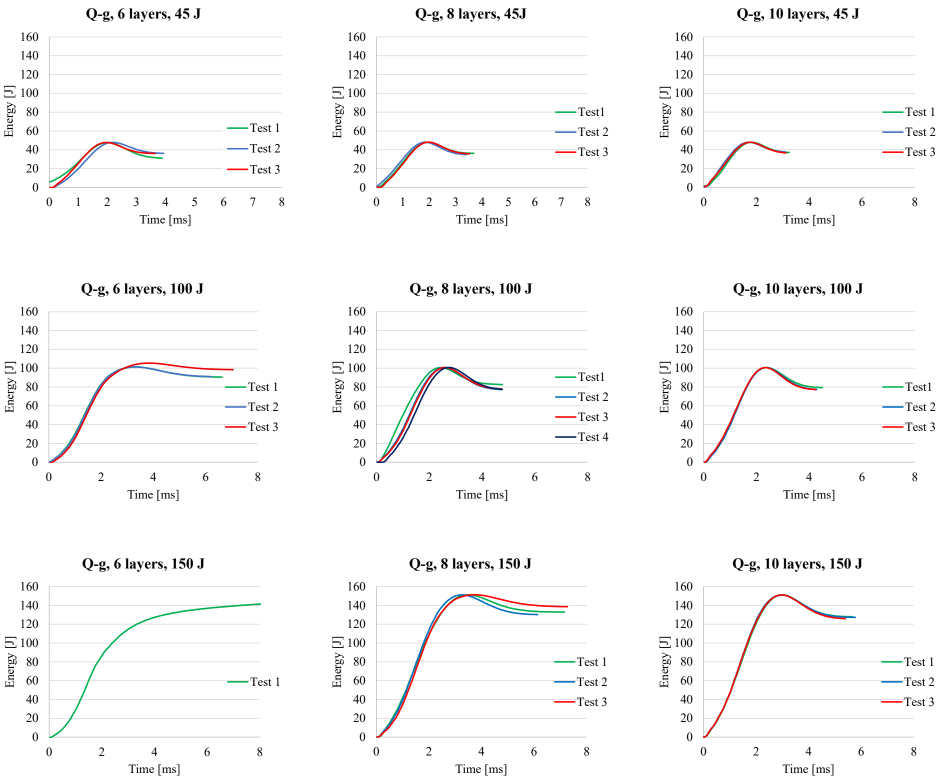

Fig. 2. Absorbed energy–time curves for quadriaxial glass fiber composites with 6, 8 and 10 layers, at impact energies of 45 J, 100 J, and 150 J.

In Figure 3, the maximum displacement increases with higher impact energy.

At 45 J, all composite types show moderate and comparable displacement values. At 100 J, the 6-layer laminates already record a sharp increase in displacement, reflecting lower stiffness and a tendency toward failure, while the 8- and 10-layer laminates maintain lower displacements due to their increased thickness. At 150 J, maximum displacement becomes very high for the 6-layer composites, indicating a loss of structural integrity, while for the 10-layer configuration the displacement remains controlled despite the higher applied energy.

These results demonstrate that stiffness increases with thickness: thicker composites withstand deformation better, reducing the risk of penetration. Thinner laminates (6 layers) are more flexible, but at the cost of reduced impact resistance.

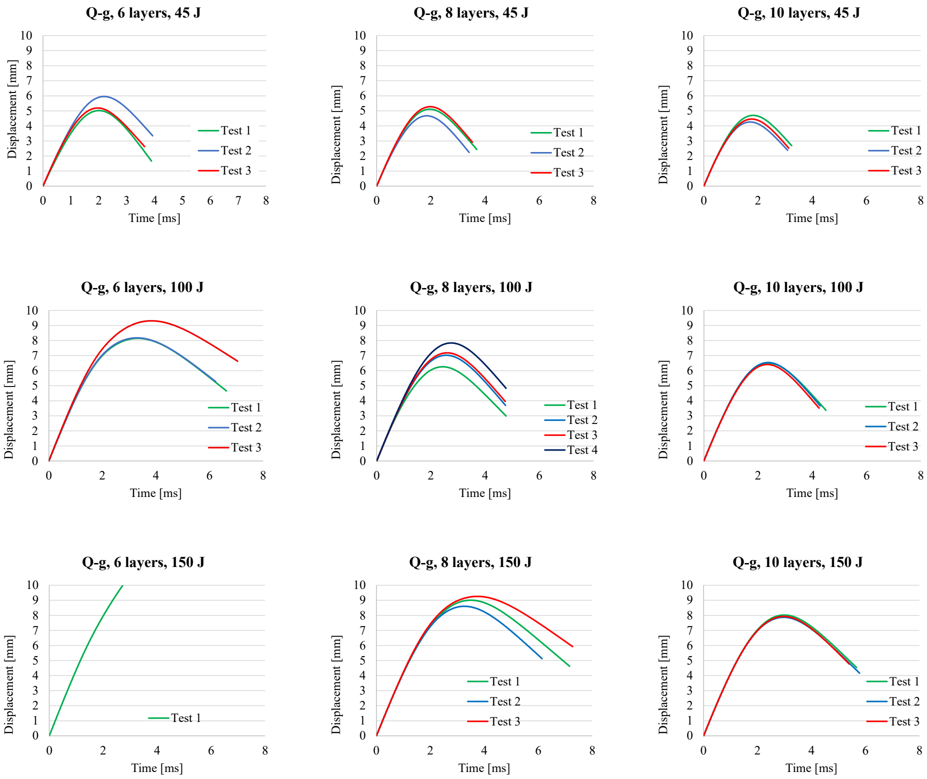

Fig. 3. Displacement–time curves for quadriaxial glass fiber composites with 6, 8, and 10 layers, at impact energies of 45 J, 100 J, and 150 J.

In Figure 4, the velocity curves illustrate how the impactor is decelerated by the composite. At 45 J, the differences between the 6-, 8-, and 10-layer laminates are minimal, with all being able to slow down the impactor within a similar time frame. At 100 J, the 6-layer composites show slower velocity reduction and oscillations after impact, indicating a less stable response. The 8- and 10-layer laminates, by contrast, decelerate the impactor more effectively, with a sharp velocity drop and controlled recovery. At 150 J, only the thicker laminates manage to significantly reduce the impactor's velocity, while the 6-layer composites fail to ensure full energy dissipation. Therefore, additional thickness proves beneficial for more efficient absorption of kinetic energy, minimizing the risk of perforation by the impactor.

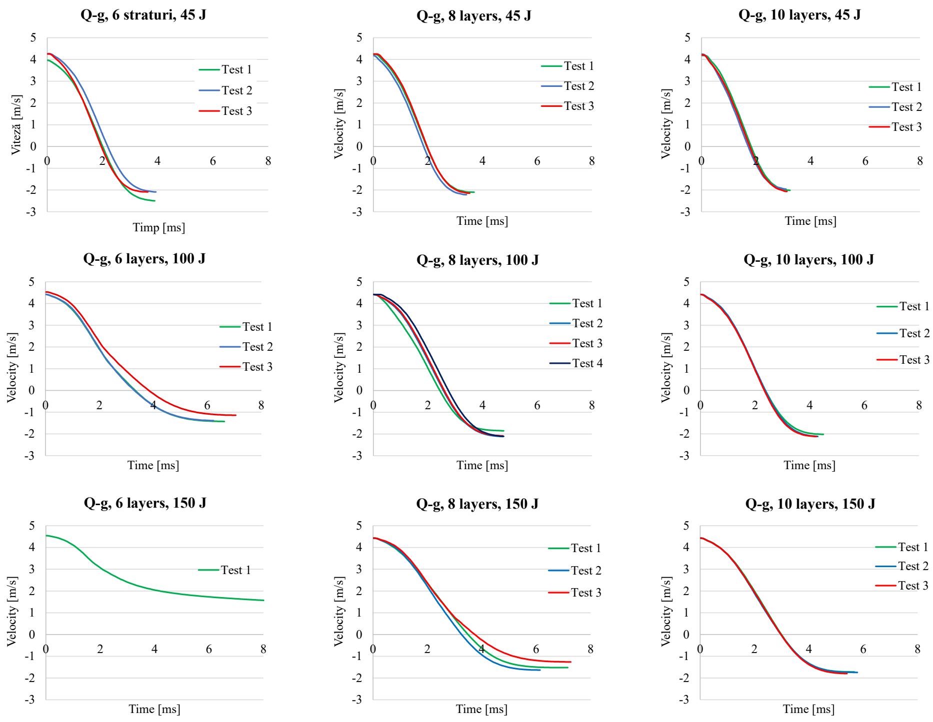

Fig. 4. Velocity–time curves for quadriaxial glass fiber composites with 6, 8, and 10 layers, at impact energies of 45 J, 100 J and 150 J.

3. Results and discussion

Figure 5 presents the representative appearance of the specimens after impact, highlighting the differences in damage as a function of the number of layers and the applied impact energy.

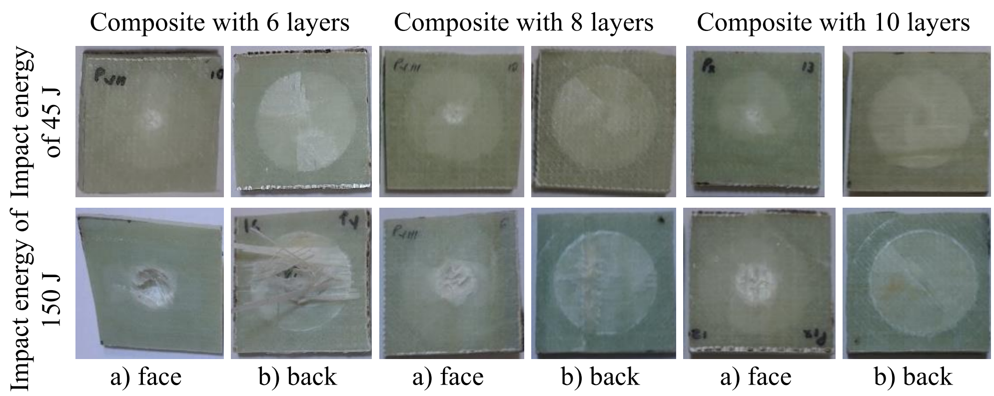

Fig. 5. Representative damage on front (a) and back (b) surfaces of quadriaxial glass fiber composites with 6, 8, and 10 layers, tested at impact energies of 45 J and 150 J.

Based on the previously presented force–time, energy–time, displacement–time, and velocity–time curves (Figures 1–4), it can be noted that both the impact energy level and the composite thickness significantly affect the behavior of the composites. However, these numerical and graphical results provide only a global view of the energy absorption and deformation mechanisms. For a more comprehensive understanding, a visual examination of the damage morphology is required, on both the impacted face and the rear surface.

In Figure 5, the differences in damage morphology are clearly visible depending on the impact energy and the composite thickness. At an impact energy of 45 J, all specimens (6, 8, and 10 layers) show a circular whitening zone on the front face, typical of microcracking and early delamination. The rear surfaces exhibit almost no significant damage, indicating that most of the impact energy was dissipated within the laminate without causing perforation. Increasing the number of layers results in less visible damage, confirming that additional thickness enhances the energy dissipation capacity.

At an impact energy of 150 J, the damage is considerably more severe. For the 6-layer composite, the specimen exhibits clear perforation and fiber breakage on the rear surface, demonstrating complete material failure. In the case of the 8-layer composite, extended delaminations and fiber pull-out are visible, though the overall integrity of the plate is partially maintained. The 10-layer specimens show the best resistance: although whitening zones appear on both front and back surfaces, no full perforation occurs, highlighting the critical role of thickness in improving impact tolerance.

In Figures 6 and 7, the force–time, absorbed energy–time, displacement–time, and velocity–time responses of the composites with 6, 8, and 10 layers are shown for impact energies of 45 J, 100 J and 150 J.

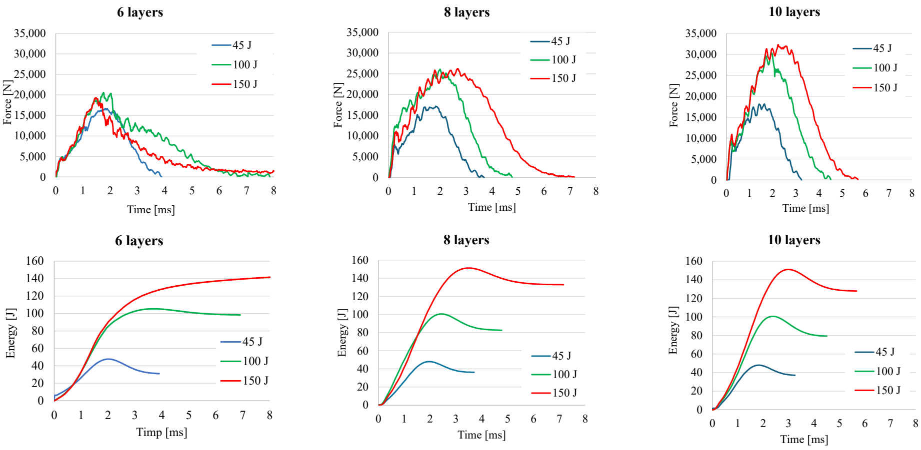

Fig. 6. Comparative plots of force and absorbed energy for composites with 6, 8, and 10 layers, tested at impact energies of 45 J, 100 J, and 150 J.

For the 6-layer composite, the behavior is strongly dependent on impact severity. At 45 J, the peak force reaches approximately 17–18 kN at ~1.7 ms, with a maximum displacement of about 5–6 mm and an absorbed energy of ~35–40 J.

Increasing the energy to 100 J raises the peak force to 21–23 kN, the displacement to ~9 mm, and the absorbed energy to ~90–95 J. At 150 J, however, the peak force drops slightly (~18–20 kN) while displacement exceeds 15 mm, and the energy curve rises monotonically without stabilization, indicating perforation. The velocity remains positive (~1–2 m/s at 8 ms), confirming that the impactor penetrated the specimen.

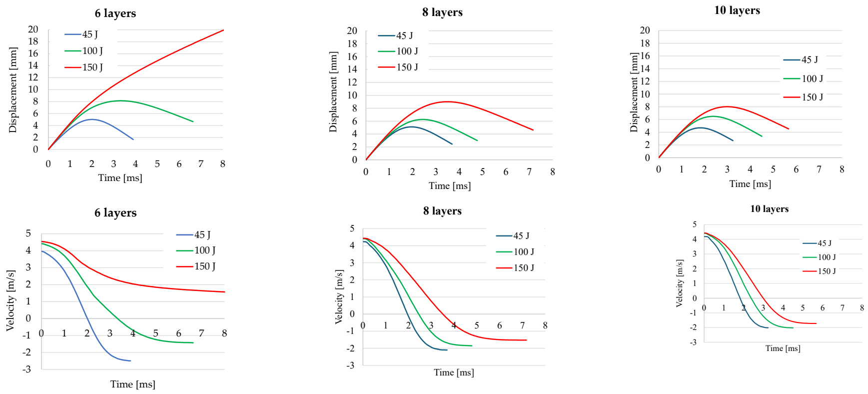

Fig. 7. Comparative plots of displacement, and velocity for composites with 6, 8, and 10 layers, tested at impact energies of 45 J, 100 J, and 150 J.

For the 8-layer composite, the response demonstrates greater robustness. At 45 J, peak force values of ~18–19 kN are associated with ~6 mm displacement and ~40 J absorbed energy. At 100 J, the maximum force increases to 25–26 kN at ~3 ms, with displacement limited to ~8 mm and absorbed energy of ~95–100 J. At 150 J, peak force values of 28–30 kN are observed, with displacement contained to ~9–10 mm and absorbed energy close to the input (~145 J). The velocity curves cross into negative values, showing elastic rebound and good impact tolerance.

The 10-layer composite exhibits the highest stiffness and damage resistance. At 45 J, peak forces of 19–20 kN are reached, with displacement restricted to ~4–5 mm. At 100 J, peak forces rise to 28–29 kN with displacement of ~6–7 mm, and at 150 J the maximum force reaches 30–31 kN with displacement limited to ~8–9 mm. In all cases, the absorbed energy matches the impact energy, and rebound is evident, demonstrating that no perforation occurs even at the highest energy.

In Figure 8, the thickness effect is directly compared for each impact energy.

Peak force values (Figure 8) increase slightly with thickness, from ~17–18 kN to ~19–20 kN. At 100 J, differences become clearer: the 6-layer composite reaches ~22 kN with 8.5 mm displacement, while the 10-layer composite withstands ~28 kN with only 5.5 mm displacement. At 150 J, the contrast is critical: the 6-layer composite fails by perforation (low rebound, displacement >15 mm), whereas the 8- and 10-layer laminates sustain forces of 28–31 kN, with controlled displacements of 9–10 mm and clear rebound. At 45 J, all composites absorb almost the entire energy, but increasing thickness reduces maximum displacement: ~5.5 mm for 6 layers, ~6 mm for 8 layers, and ~3.5 mm for 10 layers (Figure 8). The rebound is clearly noticed on velocity plots as the velocity of the impactor change sign. When v=0 the entire kinetic energy of the impactor is transferred to the composite plate that undergoes elastic and plastic deformation. A part of this energy is then transferred again to the impactor that rebounds. No change in the sign of the measured velocity reflects the perforation of the plate and the low slope of the velocity means that friction consumes a part of the impactor energy.

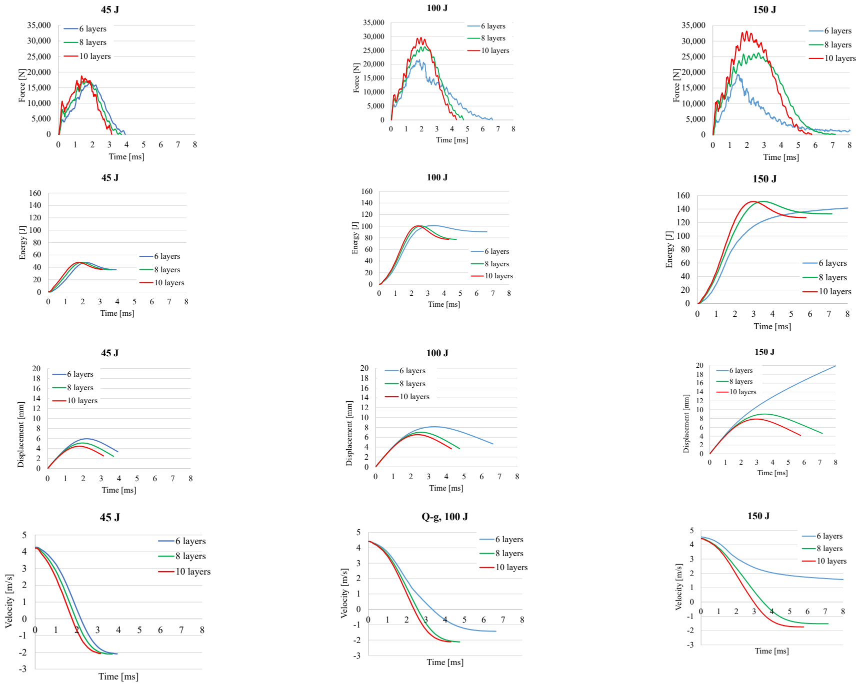

Fig. 8. Comparative plots of force, absorbed energy, displacement, and velocity for quadriaxial composites of different thicknesses (6, 8, and 10 layers), at impact energies of 45 J, 100 J, and 150 J.

Table 1. Summary of impact test results for quadriaxial glass fiber composites with 6, 8 and 10 layers, at impact energies of 45 J, 100 J and 150 J.

Thickness (number of layers)	**Energy (nominal) [J]**	**F_{max} [kN]**	**$t(F_{max})$ [ms]**	**Max displace-ment [mm]**	**Absorbed Energy [J]**	**Absorbed Energy [% of nominal value)**	**Rebound**
6 layers	45 J	17–18	~1.7	5–6	~35–40	77.7-88.8	Yes
	100 J	21–23	~2.0	~9	~90–95	90-95	Yes
	150 J	18–20	~2.1	>15	~140*	93.3	No (perforation)
8 layers	45 J	18–19	~2.0	~6	~40	88.8	Yes
	100 J	25–26	~3.0	~8	~95	95	Yes
	150 J	28–30	~3.3–3.6	9–10	~145	96.6	Yes
10 layers	45 J	19–20	~2.0	4–5	~40	88.8	Yes
	100 J	28–29	~3.0	6–7	~95	95	Yes
	150 J	30–31	~3.5	8–9	~145	96.6	Yes

*Not calculated for total perforation

To provide a clearer overview of the main findings extracted from Figures 6 and 7, the most relevant parameters – peak force, maximum displacement, absorbed energy, and velocity trends – were synthesized in Table 1.
This table condenses the graphical information into numerical values, enabling a direct comparison between composites of different thicknesses (6 layers, 8 layers, and 10 layers) under the three impact energy levels (45 J, 100 J, and 150 J). Such centralization facilitates the identification of consistent trends and critical thresholds, highlighting the combined influence of both thickness and impact /energy on the dynamic response of the quadriaxial glass fiber composites.

4. Conclusions

The experimental program conducted in this study highlighted the influence of both impact energy and laminate thickness on the behavior of quadriaxial glass fiber–epoxy composites. The results demonstrated that the repeatability of the impact tests was very good, the force–time and velocity–time curves confirming the uniformity of the manufactured samples. Increasing the number of layers systematically improved the impact resistance, as thicker laminates reached higher maximum forces, absorbed more energy, and showed longer times to failure.
The low-velocity impact response of composite laminates manufactured with 6, 8 and 10 quadriaxial prepreg layers was experimentally investigated for impact energies of 45 J, 100 J and 150 J. The following conclusions can be drawn, concerning the effect of impact energy and the number of quadriaxial prepeg layers. At 45 J, all panels exhibited a preponderant elastic response with impactor rebound. The maximum force ranged between 17–20 kN, the maximum displacement between 4–6 mm, and the absorbed energy between 35–40 J (≈80–90% of the nominal impact energy). At 100 J, the specimens showed crush damage (under the impactor) and delaminations, but still maintained rebound. The maximum force increased to 21–29 kN, displacement decreased to 6–9 mm, and absorbed energy to approx. 90. At 150 J, composite damage became severe. The composite with 6 layers was perforated, while those with 8 layers and 10 layers resisted the impact and allowed rebound. For the latter, F_{max} reached 30–31 kN, maximum displacement was limited to 8–10 mm, and the absorbed energy was approximately 145 J. Increasing the number of layers leads to a clear increase in maximum load capacity (from ≈22 kN for 6 layers to ≈30 kN for 10 layers, at 100–150 J), accompanied by a decrease in maximum displacement (from ≈9–15 mm for 6 layers to ≈6–9 mm for 8–10 layers). The absorbed energy approaches the input impact energy as the number of layers increases, indicating improved energy dissipation and reduced local damage. Thicker laminates exhibit higher stiffness and resilience, preventing perforation even under high impact energies.
The 6-layer composite was total perforated at 150 J, while 8-layer and 10-layer panels have damaged layers (on front and back of the composite), but without total perforation, confirming the protective effect of composite thickness. Damage morphology evolved from matrix cracking and local delaminations at 45 J, to fiber breakage and partial perforation at 150 J.Overall, both impact energy and laminate

thickness (number of quadriaxial prepreg layers) strongly influenced the mechanical response of these composites. The results highlight that increasing laminate thickness enhances impact resistance by raising F_{max}, lowering the maximum displacement, and improving energy absorption capacity without perforation.

References

[1] Summerscales J., *Materials selection for marine composites*, Marine Composites. Design and Performance, R. Pemberton, J. Summerscales, J. Graham-Jones (editors), Woodhead Publishing Elsevier, Cambridge, MA, United States, 2019, p. 4-30.

[2] Abramovich H., *Advanced Aerospace Materials, Aluminum-Based and Composite Structures*, 2nd Edition, Walter de Gruyter GmbH, Berlin, Germany, 2023

[3] Lu Y. C., Pilla S., *Design of Automotive Composites*, SAE International Warrendale, PA, USA, 2014

[4] Lopresto V., Langella A., *Dynamic Response and Failure of Composite Materials and Structures*, Woodhead Publishing, Elsevier, Cambridge, MA, United States 2017.

[5] Naresh K., Shankar K., Rao B. S., Velmurugan R., *Effect of high strain rate on glass fiber reinforced epoxy laminated composites*, Composites Part B: Engineering, **100**, 2016, p. 125–135. https://doi.org/10.1016/j.compositesb.2016.06.007

[6] Camanho P.P., Dávila C.G., *Mixed-mode decohesion finite elements for the simulation of delamination in composite materials* (NASA Technical Report TM-2002-211737) NASA Langley Research Center, 2002.

[7] Chu Y., Min S., Chen X., *Numerical study of inter-yarn friction on the failure of fabrics upon ballistic impacts*, Materials & Design, **115**, 2017, p. 299–316, https://doi.org/10.1016/j.matdes.2016.11.013

[8] Ingle S., Yerramalli C. S., Guha A., Mishra S., *Effect of material properties on ballistic energy absorption of woven fabrics subjected to different levels of inter-yarn friction*, Composite Structures, **266**, 113824. 2021, https://doi.org/10.1016/j.compstruct.2021.113824

[9] Meyer C. S., O'Brien D. J., Haque B. Z. G., Gillespie Jr. J. W., *Mesoscale modeling of ballistic impact experiments on a single layer of plain weave composite*, Composites Part B: Engineering, **235**, 109753, 2022.https://doi.org/10.1016/j.compositesb.2022.109753

[10] Singha M., Singha K., *Applications of textiles in marine products*, Marine Science, **2**, 6, 2012, p. 110–119. https://doi.org/10.5923/j.ms.20120206.01

[11] Johannsen T. J., *One-Off Airex Fiberglass Sandwich Construction*, Chemacryl, Inc., 1973.

[12] Castro Composites. (n.d.). 1200 g/m² Quadraxial stitched glass fabric (0º/+45º/90º/−45º), 127 cm wide. https://www.castrocompositesshop.com/en/fibre-reinforcements/1204-1200-gm2-quadriaxial-stitched-glass-fabric-0%C2%BA45%C2%BA90%C2%BA-45%C2%BA-127-cm-wide.html

[13] Sika. (n.d.). SikaBiresin® CR82 (formerly Biresin® CR82): Composite resin systems for wet lay-up. https://industry.sika.com/en/home/advanced-resins/sports-and-leisure/composite-resin-systems/composite-systemsforwetlay-up/sikabiresin-cr82.html

[14] Hoa S. V., *Principles of the manufacturing of composite materials* (2nd ed., pp. 3–5). DEStech Publications, 2017.

[15] Cirex CP-10, Airétec, https://www.airetec.fr/Agent-demoulage-ZH

[16] Ceara Cirex CP10, https://www.rompolimer.ro/produse/demulanti-agenti-lustruire/#

[17] Instron. (2009). CEAST 9300 Series: Drop tower impact systems (WB1268C). https://www.instron.com/-/media/literature-library/products/2010/02/ceast-9300-series.pdf

[18] Sutherland L. S., Guedes Soares C., *Scaling of impact on low fibre-volume glass–polyester laminates*, Composites Part A: Applied Science and Manufacturing, **38**, 2, 2007, p. 307–317. https://doi.org/10.1016/j.compositesa.2006.04.003

[19] Sutherland L. S., Shenoi R. A., Lewis S. M., *Size and scale effects in composites: II. Unidirectional laminates*, Composites Science and Technology, **59**, 2, 1999, p. 209–220. https://doi.org/10.1016/S0266-3538(98)00083-9/